TECHNICAL REPORT

PR-8

THE THERMAL CONDUCTIVITY OF A MULTILAYER SAMPLE OF UNDERWEAR MATERIAL UNDER A VARIETY OF EXPERIMENTAL CONDITIONS

QUARTERMASTER RESEARCH & ENGINEERING CENTER
PIONEERING RESEARCH DIVISION

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UNCLASSIFIED

1. Heat transfer
2. Thermal conductivity
3. Heat conductivity
4. Clothing
5. Underwear
6. Cotton textiles
7. Woolen textiles
8. Thermal insulation
9. Perspiration

I. Title
II. Series
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Project Reference:
7X99-25-001

October 1962

FOREWORD

This is the last of three reports dealing with work performed jointly by the Pioneering Research Division and the former Environmental Protection Research Division of this Center. The apparatus, experimental techniques, accuracy, and automatic control equipment have been described in the two previous reports. The present report deals with measurements made on a sample of standard underwear material (50 wool/50 cotton).

The work reported in the present paper has been supported in part by funds made available through the Thermalibrium Suit program.

A thermalibrium suit as currently visualized has a layer at or near the outside that is impervious to air, to water vapor, and to liquid water. The soldier wearing such a suit will be warmed or cooled, as necessary, by auxiliary equipment. The problem of supplying heat to or removing heat from the various parts of the wearer's body is a difficult one. The impervious layer means that sweat cannot be gotten rid of normally, by passage outward through the clothing, either before or after evaporation. Sweat will accumulate inside a thermalibrium suit unless it is removed by some special means.

The transfer of heat in the presence of large proportions of moisture is thus an important problem in the design of a practical thermalibrium suit, and is of considerable significance in the design of ordinary clothing as well. The present paper gives data on the flow of heat through underwear material under various experimental conditions. The results presented are of course only one small part of the data that must be considered and evaluated in the design of a thermalibrium suit.

S. DAVID BAILEY, Ph. D.
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Pioneering Research Division

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Scientific Director
QM Research and Engineering Command

MERRILL L. TRIBE
Brigadier General, USA
Commanding
QM Research and Engineering Command

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ABSTRACT

Results of measurements of the thermal conductivity of a sample of twelve layers of standard underwear material (50 wool, 50 cotton) are presented. Temperature was varied from about 65° to about 135° F, pressure (air) was varied from less than 0.1 mm Hg to atmospheric, and sample density was varied from about 14 to about 20 lb per cubic foot. Some measurements were made with the air removed from the sample chamber and water introduced. Measurements were made in which the air in the sample chamber was replaced by helium, or by Freon-12 (CCl_2F_2).

THE THERMAL CONDUCTIVITY OF A MULTILAYER SAMPLE OF UNDERWEAR MATERIAL UNDER A VARIETY OF EXPERIMENTAL CONDITIONS

1. Introduction

The measurements now being reported were made in the apparatus described in references (1) and (2), according to the procedures outlined in these reports. In all, 54 runs were made, of which 22 were rejected because they failed by substantial amounts to meet the established criteria for acceptability. These criteria are discussed below. All of the accepted data are given in a single table (Table 1).

The runs fall into five groups, each characterized by the quantity or property that was being varied in that particular group of measurements. A few runs fall within more than one category. In particular, runs 29 and 72 were made under conditions that we came to accept as the standard state of departure when variations were to be made. For this standard or reference state the mean temperature of the sample was 92.8°F (33.8°C), the sample thickness was 0.748 in., and the gas surrounding the sample was air at atmospheric pressure.

Purpose of Each Group of Runs. The specific objective of each group of runs is given in the list below. (Because of rejected runs, those listed are sometimes not numbered consecutively.)

	Runs
Effect of sample temperature	48-54
Effect of pressure of the air surrounding the samples	44,45, 55-68
Effect of water vapor introduced into the sample chamber	32-36
Effect of sample density	72-75
Effect of replacing the surrounding air by other gases	78-82

Accuracy. The thermal conductivity values presented in this paper are believed to be accurate to ± 2 percent, except where otherwise indicated. In reference (1) it was stated that the apparatus appeared to be capable of an accuracy of 1 percent or better. One of the principal causes of the larger estimate now being made is associated with the measurements of sample thickness. Each time the apparatus is taken apart and reassembled, the thickness of the gasket varies slightly, depending among other things on the amount of torque used to tighten the clamping nuts. The uncertainty in gasket thickness does not introduce error into measurements of sample thickness, provided measurements of the overall thickness of sample chamber, gasket, and lid are made each time the apparatus is assembled. Through error, these overall measurements were not made for the present experiments, but thicknesses were computed on the basis of an earlier set. The additional error in sample thickness resulting from this oversight is estimated as 0.010 inch. The lowered accuracy of 2 percent now being claimed is quite sufficient for our present purposes.

2. Description of Sample

The sample consisted of 12 layers of underwear material cut from a single piece of cloth obtained from Mr. Louis I. Weiner of the Textile Clothing and Footwear Division (now part of the Clothing and Organic Materials Division). The material is the standard fabric used in the Army's M-1950 winter undershirt and drawers. It is a knitted cloth, 50 percent wool and 50 percent cotton by weight. It is shrink-resistant, and both surfaces are the same. The nominal weight is 11 ounces per square yard.

The 12 circular pieces of material comprising the sample had a mean diameter of 6.31 inches and together weighed 3.028 ounces (85.84 grams). The pieces were piled up with the ribs of odd layers at right angles to the ribs of even layers. The uncompressed thickness of the 12 layers was 7/8 inch, within ± 1/16 inch. When a brass plate was laid on the pile, so that a pressure of 0.133 lb per square inch was applied, the thickness was reduced from 7/8 inch to 0.627 ± 0.007 inch. Measurement of these thicknesses made it possible to estimate what setting of the hot plate was required to insure that the hot plate made contact with the sample after the apparatus was assembled.

Sample thickness. The sample was placed in the sample chamber and the hot-plate guard-ring combination was lowered to compress the sample

to a thickness of about 0.748 inch. This value is about half way between the uncompressed thickness of the sample and its thickness under a pressure of 0.133 lb per square inch, as noted in the paragraph above. The thickness of the sample was kept near this value during most of the measurements now being reported. When the effect of sample density on thermal conductivity was being investigated, it was of course necessary to change the sample thickness in order to vary its density.

Volatile matter given off during experiments. It was necessary to evacuate the sample chamber before introducing water vapor, and also when thermal conductivity was to be measured at the lowest attainable surrounding pressure. Whenever we tried to reach the lowest pressures, we noticed that the sample gave off a substance or substances of appreciable vapor pressure that contaminated the mercury-vapor pump and also collected in the oil of the mechanical vacuum pump. The latter pump had a small oil-capacity and the oil had to be changed frequently when low operating pressures were required. Presumably the troublesome substance was given off by the wool and not by the cotton. The fabric of the sample was from a new bolt and we had not washed it. There was no evidence that the small loss of volatile matter from the sample changed its thermal conductivity.

3. Experimental Procedures

Criteria for acceptable runs. General operating procedures have been described in references (1) and (2). The first of these gives the criteria established for acceptable runs. The second gives step-by-step procedures for starting up and making a thermal conductivity run. The most important of these criteria is that a run should cover a period of at least 3 hours, during which the observed thermal conductivity varies by no more than 1 percent. This criterion has been adhered to in the present work, except where noted to the contrary.

Measuring sample thickness. Except during the earliest measurements, sample thickness was measured at least once during each run, and the thermal conductivity for that run calculated from the thickness found. Actually, there was no evidence of permanent change in sample thickness except when the thickness had been intentionally changed by manual adjustment.

Measuring pressure. If the sample chamber was in communication with the atmosphere, no pressure readings were taken. But when the apparatus was being operated at reduced pressure, either with air or water vapor present, at least one pressure measurement was made during each run. During some runs at low pressure it was necessary to measure the pressure within the sample chamber quite often, and to readjust the pressure after nearly every measurement.

Three typical runs. Values of thermal conductivity observed during three selected runs have been plotted in Fig. 1 versus the time of day. These runs were taken with air surrounding the sample, at the pressures, temperatures, and thicknesses shown on the graphs. Points joined by solid lines lie within the 1 percent limit set for acceptability, whereas points on the dashed portions of the curves lie outside this limit and were excluded when the data were averaged. Normally, all points included in the average were given equal weight. Note that run 56 shows a downward trend of k during the rating period, whereas the other two runs show an upward trend. The upward trend was more common. Runs 56 and 53 are considered good runs, while run 61, in which the change during the rating period was large and all in one direction, is considered one of the poorer runs.

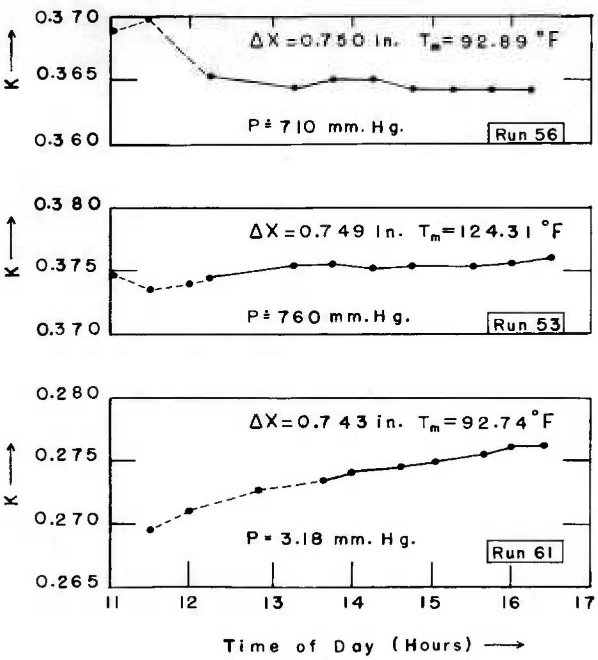

Fig. 1. Graphs showing the approach to the steady state for three typical runs. To qualify as a good run, the k value should not change by more than 1 percent in the last 3 hours.

4. Table of Experimental Data

Table 1 contains all of the accepted data. The run number is given first. Asterisks and daggers refer to footnotes qualifying the accuracy

TABLE 1. EXPERIMENTAL DATA ON THE THERMAL CONDUCTIVITY OF A 12-LAYER SAMPLE OF 50 COTTON-50 WOOL UNDERWEAR MATERIAL.

VALUES OF ΔX IN PARENTHESES WERE NOT MEASURED AT THE TIME OF THE RUN, BUT WERE INFERRED FROM EARLIER AND LATER MEASUREMENTS.

Run No.	Purpose	Ambient Gas	Pressure	Amount of H_2O	Thickness (ΔX)	Density	ΔT	$\Delta T/\Delta X$	T_m	k
			mm Hg	grams	inch	lbm. ft^{-3}	°F	°F/inch	°F	$\frac{\text{Btu in.}}{\text{°F ft}^2\text{ hr}}$
29	T, ρ, P	air	ca. 760	----	0.749	14.0	42.23	56.4	92.72	0.356
32*†	W	H_2O	----	1.0	(.746)	14.0	42.41	56.8	92.80	.311
33*	W	"	----	1.92	(.746)	14.0	42.44	56.9	92.82	.342
34*†	W	"	----	3.98	(.746)	14.0	42.49	57.0	92.84	.350
35*	W	"	----	0.5	.744	14.0	42.31	56.9	92.76	.300
36*	W	"	----	6.02	.746	14.0	42.50	57.0	92.85	.322
44	P	air	371	----	.746	14.0	42.34	56.8	92.77	.360
45*	P	"	12.6	----	.747	14.0	42.13	56.4	92.66	.319
48*	T	air	ca. 760	----	(.747)	14.0	39.75	53.2	64.48	.352
49*	T	"	"	----	.749	14.0	39.66	53.0	71.63	.353
50	T	"	"	----	.748	14.0	39.76	53.2	78.88	.354
51	T	"	"	----	.750	13.9	40.74	54.3	104.57	.369
52	T	"	"	----	.749	14.0	40.47	54.0	111.64	.371
53	T	"	"	----	.749	"	40.62	54.2	124.31	.375
54	T	"	"	----	.748	"	40.32	53.9	136.76	.381
55	P	"	600	----	.749	"	42.95	57.3	93.08	.365
56	P	"	ca. 710	----	.750	13.9	42.58	56.8	92.89	.365
57	P	"	142	----	.748	"	41.95	56.1	92.58	.359
59	P	"	50.8	----	.749	"	42.96	57.4	93.08	.351
61*	P	"	3.18	----	.743	14.1	42.28	56.9	92.74	.275
62*	P	"	1.09	----	.750	13.9	42.74	57.0	92.97	.229
63*	P	"	0.320	----	.751	13.9	41.64	55.4	92.42	.203
64	P	"	.168	----	.750	13.9	42.61	56.8	92.90	.193
67	P	"	.087	----	(.747)	14.0	42.51	56.9	92.86	.165
68	P, W	"	.023	0	.747	14.0	42.56	57.0	92.88	.152
72	T, ρ, P	air	ca. 760	----	.746	14.0	40.69	54.5	91.94	.360
73	ρ	"	"	----	.655	16.0	40.43	61.7	91.82	.405
74	ρ	"	"	----	.587	17.8	40.01	68.2	91.60	.446
75	ρ	"	"	----	.528	19.8	40.82	77.3	92.01	.477
78	M	He	"	----	.657	15.9	42.69	64.9	92.94	1.299
79†	M	"	"	----	.658	15.9	41.96	63.8	92.58	1.308
80	ρ, M	air	"	----	.657	15.9	42.55	64.8	92.88	0.413
82	M	Freon-12	"	----	.657	15.9	45.07	68.6	94.14	.235

* Accuracy less than normal because rating period was less than 3 hours.
† Accuracy less than normal because change of k during rating period exceeded 1 percent.

of part of the runs. In the column headed "Purpose" the letter T refers to temperature; ρ, to density; P to pressure of surrounding air; W, to water introduced; and M, to molecular weight of surrounding gas. Each symbol refers to a related group of measurements, as explained more fully below as each group of measurements is discussed. The remaining symbols are self-explanatory; ΔX is of course the sample thickness, ΔT the difference between the hot-plate and cold-plate temperatures, and T_m the average of these two temperatures.

5. Temperature Dependence of the Thermal Conductivity

A series of measurements of thermal conductivity of the sample were made, with the mean temperature of the sample (T_m) varied. The sample was surrounded by air at atmospheric pressure and its thickness was not varied. The results are plotted in Fig. 2 which shows thermal conductivity (k) as a function of T_m. In Table 1, the 9 runs represented in Fig. 2 are marked by the letter T.

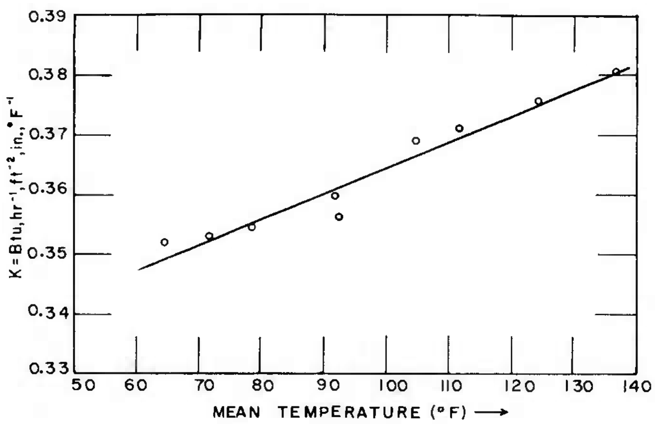

Fig. 2. Dependence of thermal conductivity of the underwear sample on temperature.

The data have been represented by a straight line, although a curve slightly concave upward might be preferred by some. The thermal conductivities shown in Fig. 2 range from about 0.35 to about 0.38 Btu in. per ^{o}F ft^2hr.

For comparison we give a value obtained by Wing and Monego (3) on standard underwear material (wool-cotton). Using a Cenco-Fitch thermal

conductivity apparatus with the hot plate at 212° F, and observing the rate of rise of the temperature of the other plate, they found a conductance of 4.47 Btu per °F ft²hr, for an unwashed sample 0.082 inch thick. Multiplying these two numbers gives a thermal conductivity of 0.367 Btu in. per °F ft²hr. The cold plate of the apparatus was initially at room temperature, which would make the initial mean temperature of the sample about 140° F. This would rise as the measurement proceeded and was perhaps 150° F on the average.

Extrapolating the curve of Fig. 2 to 150° F gives a thermal conductivity of about 0.387, which is 5 percent higher than the value of Wing and Monego. This is reasonably good agreement, considering all the differences in the two methods of measurements. Wing and Monego give a few additional measurements that show approximately the same order of agreement with our results.

6. Change of Thermal Conductivity with Pressure of the Surrounding Air

It has long been known that the thermal conductivity of air and other gases is nearly independent of the pressure of the gas, at a given temperature, provided the pressure is sufficiently high. It is assumed that convection and radiant heat transfer are absent or that corrections are made for them. As the pressure is reduced, a situation is reached in which the mean free path of the gas molecules is of the same order of magnitude as the distance across which heat transfer is being measured. In this region the thermal conductivity depends strongly on pressure. However, if the pressure is lowered still further, the gas becomes so rarefied that the heat transferred by it becomes negligible compared to what may be transferred by radiation.

Fraction of sample occupied by interstices. The statements above refer to the conductivity of a gas alone. In the experiments about to be described, the specimen is a cloth sample with the interstices filled by air. Using the data given in Section 2, the fraction of the specimen occupied by the fibers themselves will be calculated. The remainder of the specimen consists of interstices occupied by air or some other gas.

The sample had the form of a cylinder, with flat surfaces of area 31.3 sq in., and a height that, during most of the measurements, was

about 0.748 in. The sample volume at this thickness was 23.4 $in.^{3}$ and its bulk density was 14.0 lbm ft^{-3}. Reference (4) page 128 gives the density of cotton fibers as 1.50 g cm^{-3} and that of wool fibers as 1.32 g cm^{-3}. From these values and from the known masses of wool and cotton fibers present (42.92 grams of each) it was calculated that the fibers themselves occupy 16 percent of the space in the sample, leaving 84 percent for the interstices filled by air.

Role of accommodation coefficient. In a sample of this nature, the region of appreciable dependence of thermal conductivity on gas pressure is shifted to some extent toward higher pressures, as compared with the conductivity of the gas with no fabric present. The mean free path of gas molecules becomes equal to the distance between fiber particles at a higher pressure, and in addition the accommodation coefficient plays a more important role. Most gas molecules, when they strike a solid surface, do not come completely to the temperature of the surface because their accommodation coefficient on that surface is less than unity. In a fabric the flowing thermal energy must be transferred from the gas to a solid surface and out again many times before it traverses the fabric. Hence the effect of the accommodation coefficient is multiplied many times over.

The general shape of the curve of thermal conductivity of a fabric sample as the air pressure within it is reduced is well known. The curve of k plotted versus log P (this shows the phenomena most conveniently) is sigmoid in shape. However, the pressure range in which the thermal conductivity of a particular sample changes most rapidly can be found only by experiment.

Dependence of k on pressure. Figure 3 shows the dependence of k for the present sample on the pressure of the surrounding air. The points plotted in this figure correspond to the runs in Table 1 marked P in the "Purpose" column. Reduced pressures were obtained by pumping out part of the air with a vacuum pump. Measurements at pressures down to about 5 mm Hg are comparable in accuracy with most of the data being presented. Increasing difficulty was experienced at lower pressures because the pressure could not be held sufficiently steady, and because of the greater importance of the volatile substances given off by the sample.

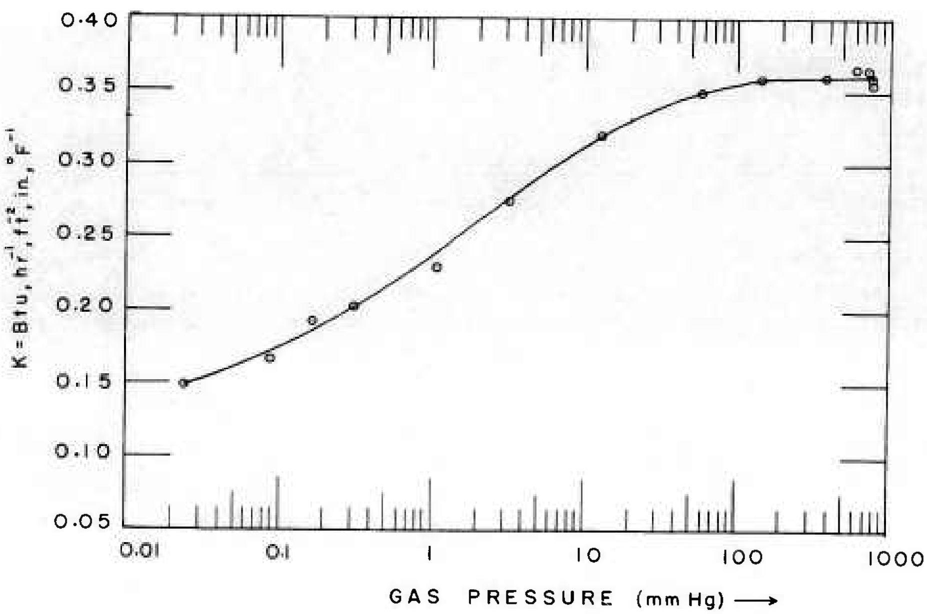

Fig. 3. Dependence of thermal conductivity of the underwear sample on the pressure of the surrounding air.

During most of the measurements, the gas pressure within the apparatus was measured at some point on the line connecting the sample chamber to the pump with which gas was removed. At pressures below about 3 mm Hg it was necessary either to pump continuously or to withdraw the gas from a connecting volume at frequent intervals, in order to keep the fractional change in pressure within acceptable limits. The rate of pressure rise was measured in an experiment described in the next section, with water present in the apparatus, and found to be about 0.34 mm Hg per hour, but there is some indication that the rate may have been smaller when only air was present in the sample chamber.

The pressure drop in the line interfered with pressure measurements during continuous pumping. Removal of the accumulating gas in batches also made it more difficult to get good pressure readings.

Near the end of the present investigations a second line connecting to the sample chamber was installed. The manometer or McLeod gage was connected to this line, which carried no flow to the pump. Thus the true pressure in the sample chamber could be measured.

The thermal conductivity of the sample at atmospheric pressure is about 0.36 Btu in./^{o}F ft^{2}hr. To reduce k to half this value requires the pressure to be reduced to the order of 0.1 mm Hg.

7. Thermal Conductivity when the Gas within the Sample is Water Vapor Only

Measurement with varying amounts of water present in the sample, either in the form of liquid or vapor, was the most important single objective of the present research. Unfortunately, the measurements made for this purpose are less satisfactory than those obtained when other experimental conditions were varied.

Method of measuring and introducing water into apparatus. A system, shown in Fig. 4, was devised for measuring and introducing water into the apparatus. This system worked satisfactorily when the apparatus had been well evacuated, but as volatile products from the wool began to build up, the rate at which water could be transferred often became very slow.

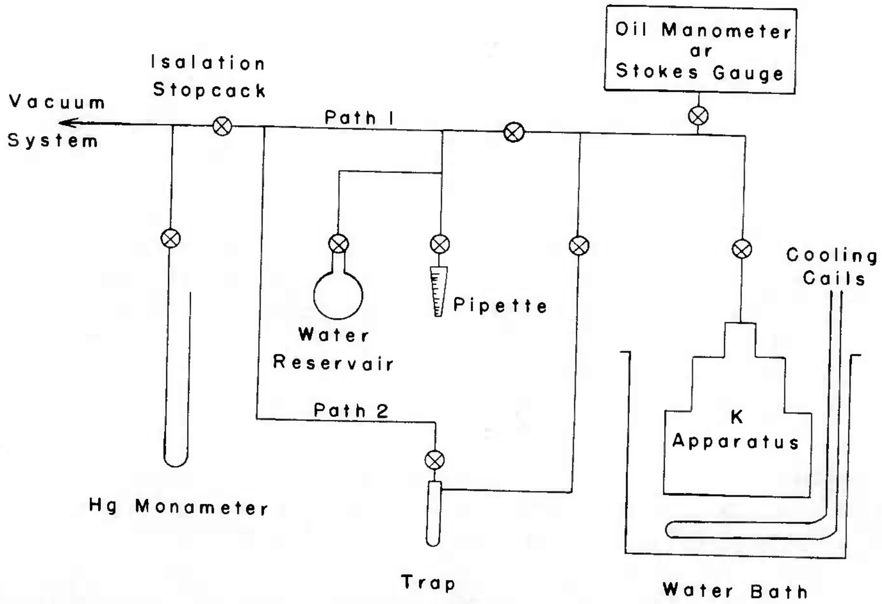

Fig. 4. System for introducing measured amounts of water into the sample chamber.

The mode of water transfer was by evaporation and condensation. Water to be introduced into the apparatus was first transferred from a reservoir to a smaller measuring chamber of 5 ml capacity, wherein the level of the condensed water could be read to the equivalent of about 0.01 gram. This chamber was constructed from a small Pyrex glass pipette. During transfer the reservoir was heated slightly and the measuring pipette cooled, either with an ice bath or with something even colder. The temperature of the reservoir must not rise much above room temperature or water vapor will condense everywhere in the lines rather than just in the measuring pipette.

After the measuring pipette was filled and the level observed, the desired amount of water was transferred to the sample chamber by cooling it and warming the measuring pipette. Transfer rates of about 1 gram in 25 minutes were attained.

Since the sample chamber was evacuated before water was distilled into it, the gas within the fibers at first consisted solely of water vapor. But as time went on the volatile components in the wool increased in concentration so that a small part of the atmosphere within the sample consisted of these volatile components.

The presence of substances other than water vapor was evident because it was much more difficult to distill water out of the sample chamber after it had been present for several days than it was to distill it in. The products given off by the wool were not condensed under the conditions of distillation and tended to block the transfer lines. In fact, although a small amount of water was distilled out of the sample chamber, the rate was so slow that we abandoned this procedure, and pumped both water and noncondensables out with a vacuum pump.

Heat transfer by evaporation and condensation. After the desired amount of water had been transferred to the sample chamber, the "thermal conductivity" was measured in the usual way. The observed heat transfer is partly, but not entirely, due to thermal conduction through a composite sample consisting of underwear fabric with water vapor in the interstices. It is known that heat transfer can also occur by another mechanism. In this mechanism, liquid water flows by capillary action from the cold plate to the hot plate, the fabric acting as a wick. As the liquid approaches the hot plate, it evaporates. The vapor flows back toward the cold plate and recondenses on or near it.

Because of the heat of vaporization, the water vapor has a much higher enthalpy than the liquid. Hence the vapor carries more heat toward the cold plate than the liquid carries away from it, and an augmentation of heat transfer is caused by the mass transfer.

The thermal conductivity (resulting from all modes of heat transfer present) is plotted in Fig. 5 as a function of the amount of water introduced. The runs represented by plotted points are identified in

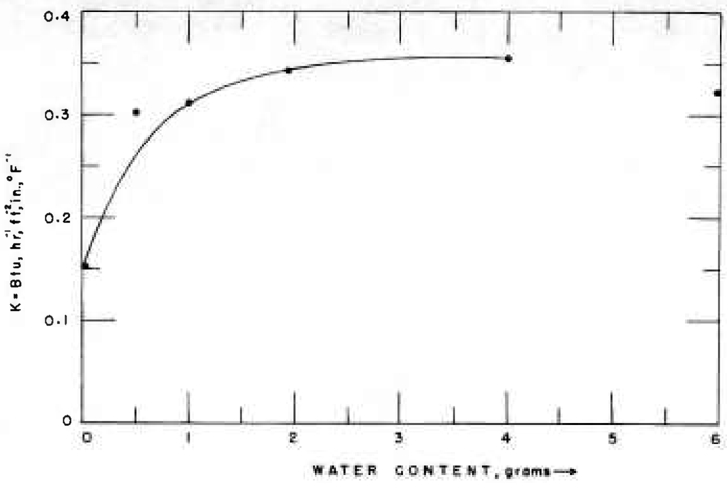

Fig. 5. Dependence of thermal conductivity of the underwear sample on the amount of water introduced into the sample chamber. Air was removed before water was introduced.

Table 1 by the letter W. The smallest amount of water introduced was 0.5 gram. The point corresponding to zero water content (run 68) was obtained with the apparatus evacuated. It is the point for the lowest pressure obtained in the measurements at reduced pressures.

The question immediately arises as to how much of the water introduced is present in the vapor phase, and how much is liquid water. An estimate of the volume of the sample chamber and the connecting lines, mostly based on known dimensions, showed that a volume of about 1440 cm^3 had to be filled with water vapor before any liquid could condense. The cold-plate temperature, for all of the points plotted in Fig. 5, was about 71.6° F (22° C). At this temperature, the vapor pressure of water is 19.8 mm Hg. Assuming that the available space is filled with water vapor at this pressure, only about 30 mg of water is required. Hence the amount of water required to saturate the vapor space is almost negligible.

It was assumed while the measurements were in progress that there was free water present in the sample chamber, except perhaps at the very lowest amounts of water introduced. This assumption is in doubt, however, as the calculations below indicate. The capacity of the sample to adsorb water was not calculated until after the measurements, and was simply underestimated.

Calculation of water adsorbed. The total weight of the 12-layer sample, 85.84 grams, was determined after the apparatus had been opened and the sample had been exposed to laboratory air for several weeks. It therefore includes an unknown amount of adsorbed water. For convenience, however, the amount of water that the sample can adsorb will be computed on the assumption that 85.84 g is the bone-dry weight.

In runs 32 to 36, in which water was present in the sample chamber, the mean temperature was 92.81° F (33.78° C). The adsorption will be calculated at this temperature. (Actually there is a steep temperature gradient across the sample, but a calculation based on the mean temperature should give a satisfactory rough estimate.) The pressure of water vapor in the sample chamber will as above be taken as 19.8 mm Hg, corresponding to saturation at the cold-plate temperature. At the mean temperature of the sample, the saturation pressure would be 39.4 mm Hg, whence the relative humidity at the mean temperature is 50.3 percent. It must be remembered that if there is no free water at the cold-plate temperature, the relative humidity will be lower than the value calculated.

In the Handbook of Textile Fibers [reference (4) p. 194, 196] we find that at 92.81° F and a relative humidity of 50.3 percent, cotton will adsorb water equal to about 6.1 percent of its dry weight and wool will adsorb water equal to about 12.5 percent of its dry weight. Under the assumed conditions, the cotton in the sample (42.92 g) will adsorb 2.62 g of water and the wool (also 42.92 g) will adsorb 5.36 g, the total adsorption being 7.98 g.

This is more than the maximum amount of water introduced, and so we must remain uncertain as to whether there was any free water present. One may assume that the sample was not dry when introduction of water was started, but it had been well evacuated and it seems doubtful if much water could have remained on the sample.

Difference between first 3 and last 2 runs. The 5 runs made with varying amounts of water in the sample chamber fall into two groups. The first group consists of runs 32, 33, and 34; these were made at water contents of 1.0, 1.92, and 3.98 grams respectively. In Fig. 5 these points fall on a smooth curve, indicating self-consistent data. The curve passing through them has been extended to the point of zero water content observed with the apparatus evacuated. Starting with the apparatus evacuated, 1.0 g of water was introduced and run 32 made. Additional water was added, and run 33 was made; the process was repeated and run 34 obtained.

After run 34, an attempt was made to remove a known amount of water but the removal was too slow. Hence the water in the sample chamber was pumped out and discarded. After the apparatus had been evacuated, 0.5 g of water was introduced and run 35 was made; this was followed by the introduction of additional water and the making of the final run of the series, run 36.

It is clear that there was some change in the sample or in the experimental conditions associated with the evacuation of the sample chamber and removal of the water after the first three runs. Run 35 gave a thermal conductivity nearly 15 percent higher than the curve representing the first set of measurements, whereas run 36 appears to be too low. The cause of the difference between the two groups of runs was not established. It seems plausible to associate it with the buildup of volatile components given off by the wool. The experimental accuracy was lower for the measurements made with water in the sample chamber than for other measurements. As indicated in Table 1, none of the runs in this series fully satisfied the criteria laid down for acceptability, since their rating periods were too short.

Estimating rate of rise of pressure of noncondensables. Some observations were made to give a rough measurement of the rate of buildup of pressure within the apparatus, resulting either from the giving off of volatile material by the sample, or from leakage of air into the sample chamber. In the early stages of the present measurements, a great deal of trouble was experienced in getting the sample chamber vacuum-tight, and several leaks were found and repaired. It appeared that all leaks had been stopped, but we were never quite sure of this. The observations about to be described measure the rate of increase of pressure due to gases given off by the sample and that due to any leaks that may have remained.

The rate of pressure rise was measured by observing the pressure in the combined volume of the sample chamber and vacuum system. The sample chamber had been isolated for 72.6 hours during which time the pressure had been building up. After opening the stopcock between the sample chamber and the vacuum system, the pressure was found to be 36 mm Hg. Assuming this to be due to saturated water vapor plus noncondensables, it was deduced that the pressure in the sample chamber before the stopcock was opened was 24.8 mm Hg due to noncondensables plus about 22 mm Hg due to saturated water vapor. The latter figure depends upon the cold-plate temperature. The rate of rise of pressure of noncondensables was thus 0.34 mm Hg per hour.

The above estimate is based on the assumption that the sample chamber contained some free water in contact with the cold plate. Computations of the amount of water that could be absorbed by the sample have made it questionable whether there actually was free water in the chamber. If all the water was partially bound to the sample, its vapor pressure would be lower than that of free water, and the pressure of 24.8 mm Hg for noncondensables should be increased.

It will be necessary to devise a modified experimental technique before definitive results on the thermal conductivity of our sample in the presence of water can be obtained. One possibility is to work in the presence of air, that is, with the total pressure equal to atmospheric, but this will greatly retard the motion of water vapor.

In spite of the confusing nature of the data obtained with water present, one rather interesting fact is evident. The thermal conductivity of the sample at 3.98 grams water content (run 34) is 0.350 Btu in./$^{\circ}$F ft^{2}hr. The pressure of water vapor is about 20 mm Hg. When the surrounding gas is air at this pressure, the thermal conductivity is, from Fig. 3, about 0.33, which is 6 percent lower. But if gas alone were present, the water vapor would have a <u>lower</u> conductivity than the air, by a factor of about 0.68. See for example Hilsenrath <u>et al</u> (5). The water introduced has been able to overcome the lowered conductivity of the gaseous phase and raise the conductivity of the wet sample above that of the equivalent air-filled sample.

It may be that water flow involving capillary action, vaporization, reverse flow of vapor, and condensation is responsible. On the other hand, water may produce better thermal contact between the fibers of the fabric, and enhance heat flow primarily in this way.

8. Change of Thermal Conductivity as Sample was Compressed

A series of measurements was made in which the thickness of the sample was varied. The variation in thickness was obtained by screwing down on the hand wheel that produces motion of the hot-plate guard-ring combination. No layers of sample were inserted or removed. The gas inside the sample chamber was air at atmospheric pressure, and the mean temperature of the sample was held near to 92.2° F (33.4° C).

The results of this series of measurements are shown in Fig. 6, and the runs represented are identified in Table 1 by the letter ρ. In Fig. 6, k is plotted versus sample density. The density was determined from the known weight of the 12-layer sample and its known dimensions. Only the thickness varies from one plotted point to another.

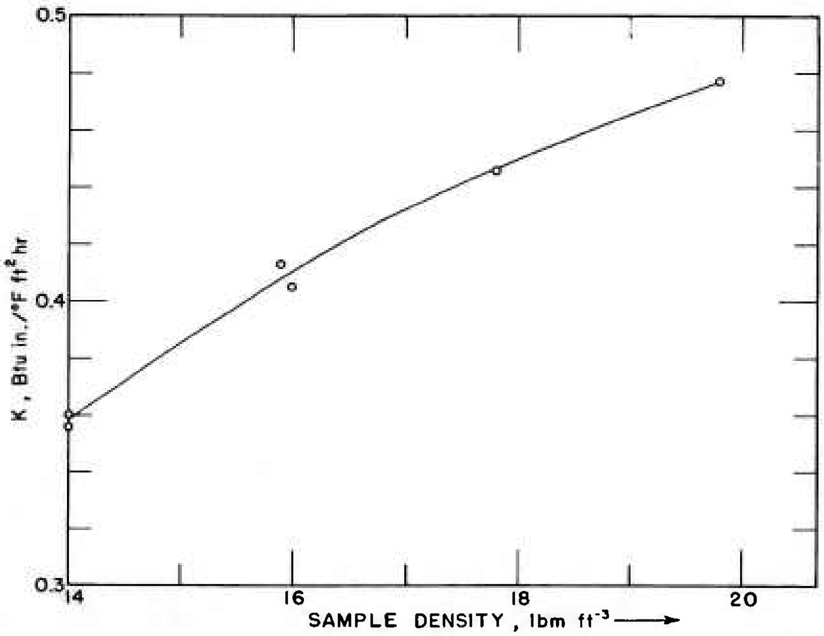

Fig. 6. Dependence of thermal conductivity of the underwear sample on density. Changes in density were produced by compressing the sample.

It is usually found that when a loose, fibrous material is compressed, its thermal conductivity falls, passes through a minimum, and then rises. The falling phase is explained (see for example reference (6) p. 75-84) as due to the gradual suppression of convection in the air within the sample. The rising phase is explained by the fact that the actual fibers of the porous material are better conductors than air. Hence the squeezing out of the air raises the conductivity, once the mechanism of convection is suppressed. This explanation leaves out the effect of radiative heat transfer but it appears to account for the major changes observed.

In Fig. 6, the thermal conductivity rises with increase in density. The minimum of thermal conductivity presumably lies at densities lower than any attainable in the measurements. A full curve in which k falls, reaches a minimum, and subsequently rises, could perhaps be observed if the material were unraveled and the ravelings measured over a wider density range, including densities to which the present sample would not expand. The change of density attainable in the present experiments was about 40 percent. At the greatest density the compressive force exerted on the sample had become large enough to put the apparatus under as great a strain as was considered advisable.

When the measurements at the highest density had been completed and the sample was allowed to return to its original thickness, the thermal conductivity was found to be about 5 percent greater than before the change of thickness. The cause of the change is not known. Possibly the mechanical structure of the sample was changed in some way. Another explanation may be the fact that the sample thicknesses at the three measuring stations for this last measurement did not agree well. The values observed were 0.698, 0.702, and 0.762 inches. The maximum difference of 0.064 inch is about 4 times as large as is considered normal. Just how the inequality would produce an increase in k is not known. It is possible, but not probable, that there was an air space above part of the sample in which convection could occur. Because of this possibility the high value (run 76) was rejected, and the remaining runs (77 to 82) were made after partially recompressing the sample.

9. Effect of the Ambient Gas on Thermal Conductivity

In the final set of experiments, the thermal conductivity of the sample was measured in an atmosphere of helium, then in air, and finally in Freon-12 (CCl_2F_2). The gas was in each case at atmospheric

pressure and the temperature was held near 92.1° F (33.4° C). For the reasons mentioned in the preceding section, the sample thickness was kept at approximately 0.657 inch, rather than at the larger value adopted for most of the measurements. The results are shown in Fig. 7, and the runs represented are identified in Table 1 by the letter M.

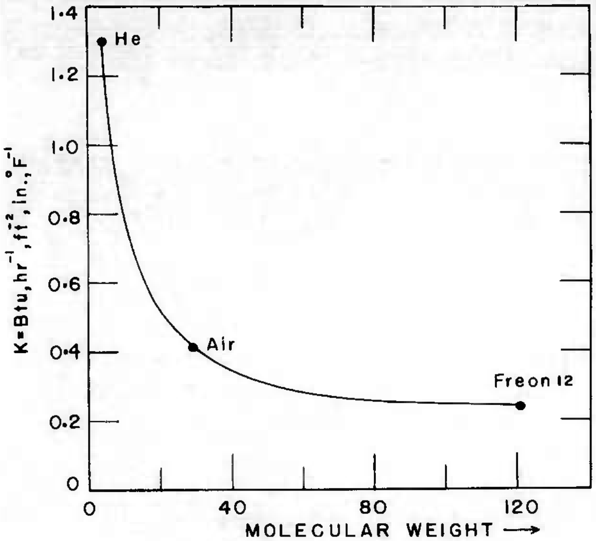

Fig. 7. Dependence of thermal conductivity of the underwear sample on the molecular weight of the surrounding gas.

Note that the points for runs 78 and 79 coincide in the figure. The conductivity falls as the molecular weight of the gas increases, but the wool and cotton of the sample have a substantial effect. For example, the sample in an atmosphere of helium has a conductivity of 1.30 Btu in./°F ft²hr. This is about 0.28 higher than the conductivity of pure helium gas. In air the conductivity is 0.41; this is about 0.23 higher than the conductivity of pure air.

If one is looking for a good insulator, fabric in an atmosphere of Freon-12 is better than the same fabric in an atmosphere of air. However, there will be no great improvement in using gases of still higher molecular weights, since the residual conduction of the fabric itself remains.

10. Summary

The present report gives the thermal conductivity of the same sample under a large number of experimental conditions, involving changes in temperature, pressure, amount of water present, sample density, and nature of the surrounding gas. For this reason it should serve a useful purpose to anyone concerned with the flow of heat under a variety of conditions, such as might be encountered in a thermalibrium suit. The fact that all measurements reported refer to the same sample

should give them greater validity than if the dependence on each parameter had been taken from a separate reference in the literature.

11. Acknowledgments

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